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Who Needs Baryon Spectroscopy?

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ABSTRACT

What is a baryon? What is a quark and what is its mass? Who needs the bag? How can baryon models help us learn new physics? Is there any baryon physics left after the Isgur-Karl Model? Are mesons and baryons made of the same quarks? Can multiquark spectroscopy survive the baryonium catastrophe? What can we learn from precise measurements of baryon magnetic moments?

I. Introduction - What is a Baryon?

A detailed summary of this conference is impossible and I do not attempt it. Instead I report my own overall impressions of the conference, emphasizing those aspects which I feel are important and not covered elsewhere in these proceedings with apologies to those who think that other aspects are more important.

There is not much to say about the material covered in the first day. Everything that we really know about baryon structure comes from experimental data, painstakingly accumulated and analyzed. The analyses presented are crucial for a proper understanding of baryon spectroscopy and structure, but a better way must be found to present this information. There should be specialized sessions where the experts actively engaged in partial wave analyses and accumulation of data can thrash out their differences. This can then be followed by one or more longer review talks, understandable to nonexperts, giving a general overview of the state of the art, and pointing out the difficulties and the problems in those

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areas where the experts still disagree. Trying to do everything at once on the first day of this conference left nonexperts like myself with a confused blur of rapidly changing transparencies and no understanding of what it all means.

The second day began with almost religious fervor and the emphatic proclamation that QCD is the true religion and De Rujula, Georgi and Glashow[1] are its prophets. This was followed by the suggestion that Isgur and Karl[2] had brought the field of baryon spectroscopy to an end with a model that predicted everything as well as could be expected so that nothing further could be learned. I counter this approach by posing a number of iconoclastic questions. Was there physics before De Rujula, Georgi and Glashow? How do we know that QCD is the right theory of hadrons and strong interactions? How can we test QCD, when nobody knows how to calculate properties of hadrons from QCD? Is there any physics left to do after Isgur and Karl? And finally to sum it up, who needs baryon spectroscopy?

Examining these questions leads to more questions. What is a baryon? QCD suggests that baryons are made of quarks interacting with gluons. But how many quarks and how many gluons? No one has yet succeeded in obtaining the answer from QCD. There are parton models with three valance quarks, an ocean of quark-antiquark pairs and a gluon component. There are constituent quark models with three quarks and nothing else. There are many different versions of parton models and constituent quark models. The three constituent quarks can be put into a bag or they can be allowed to interact with various kinds of potentials. There are models with two-body forces and models with three-body forces.

There is also the question what is a quark and what is its mass? A constituent quark is sometimes pictured as a bare quark with a gluon field. Another picture is a monopole in a superconducting vacuum. Bag models use zero mass quarks. Potentials models tend to use quarks with a mass of about 300 MeV. But where does this mass come from?[3,4] The mass of a quark with a gluon cloud can be compared with the mass of an electron which carries a Coulomb field with it. Early attempts to calculate the electron's mass by computing the energy in the electromagnetic field failed because of ultraviolet divergences which were not understood. But the long range contribution of the Coulomb field to the electron's mass was easily seen and calculable. When a positron and electron are brought close together to form positronium, the mass of the two electron system is less than the mass of two electrons. The gain in potential energy is easily calculated from the energy in the Coulomb field at large distances. A moving electron must carry with it the inertial mass in the Coulomb field going out to infinity. An electron-positron pair no longer has this field at infinity because the contributions from the opposite charges exactly cancel. The Coulomb energy of the electron-positron pair is exactly equal to the gain in energy from the reduction of the field at large distances.

Even though we think of an electron as a point particle, its Coulomb field goes out into all space and has energy density and momentum density. The mass energy and momentum of an electron depend not only on the immediate neighborhood of the electron, but also on its environment. This effect should be even stronger for a quark with a color field. The nonabelian nature of color, which leads to asymptotic freedom at short distances and infrared slavery at long distances gives a potential with a long range part increasing with distance rather than decreasing like a Coulomb field. An isolated quark (if they exist) would have a very large mass because of the large energy in the field at large distances.

This large mass is no longer present in a color singlet hadron. The color fields of the quarks cancel at large distances, like the electromagnetic field from positronium. Thus the dependence on its environment of the mass of a quark which determines its inertia and kinetic energy is greater than for the analogous state of the electron.

We can envision a picture of a hadron in which each constituent quark carries its own share of the colored gluon field within the hadron and has an effective mass determined by the gluon field. This gives an effective mass for a quark which is roughly 1/3 of the mass of a baryon. In this picture the mass of a quark, as measured in an experiment which transfers energy and momentum to the quark, depends on how much of the quark's associated gluon field recoils with it and contributes to its inertia. In deep inelastic electron scattering, the process is assumed to take place so rapidly that the field does not recoil with the quark and the quark effectively has zero mass. An isolated quark would carry all its gluon field with it when its momentum is changed and would have a very high mass, infinite in models where quarks are permanently confined. In the processes studied in baryon spectroscopy, the quark seems to carry with it a gluon field which consistently gives its share of the mass of the baryon, about 300 MeV.

An alternative picture of a hadron as a bound state of several monopoles in a superconductor leads to a different picture of the quark mass. The quarks have zero mass and they are confined by the energy required to produce the phase transitions in the superconductor. The region in which this phase transition occurs is the bag, and there is a bag energy which comes from the transition energy between the superconducting state and the normal state in the volume of the bag.

So far different pictures and models have been used with varying success for the description of quarks in hadrons. But there is no derivation from first principles to justify any particular picture and no convincing experimental agreement to demonstrate that one model is the correct model.

II. How Can Baryon Models Help Us Learn New Physics?

Most physicists today believe that QCD is the correct theory for strong interactions but it still may be wrong. However, even if QCD is right nobody knows how to use it to calculate the properties of the observed baryons. Drastic approximations are needed to get results. Which approximations are good and where do they apply? The models used to get answers all leave out much of the physics. They work in those areas where the physics left out is not important. By investigating where they work and where they break down perhaps we can learn something about the underlying physics.

Physics is an experimental science. We discover new things by doing good experiments. Theoretical models help to understand experiments and guide experimentalists to new, fruitful experiments. In this respect, the nonrelativistic quark model has been very successful. Many experimental results otherwise not related have been brought together and described by this model and many new predictions and suggestions for new experiments have been made. However, the bag models have not yet proved themselves. Bag model calculations generally only reproduce results already known from the nonrelativistic quark model. Their predictions and suggestions for new experiments have not yet been fruitful.

Who needs the bag? Is it only a kind of ether with no real existence in nature, used as a crutch to guide the intuition of physicists? Is it something like the nuclear shell model central potential, a convenient mathematical device to simplify calculations of bound states, or is there real physics in the bag describing a phase transition in the vacuum between two regions, the interior and the exterior of the bag? So far there are no answers to these questions. Bag model calculations tend only to show that they can also get results obtainable without the bag. It would be interesting if the presence of real new physics in the bag could be demonstrated, either by new experimental predictions or by derivations of this kind of phase transition from a more fundamental theory.

The principal objective in the use of any model is to learn more physics. Should we be happy if our model works to 15% or 10% or 5%? This is the wrong question. The right question is what physics are we learning by the way the model fits the experimental data. Deviations of 10% or 5% should not be dismissed because the model is only expected work to 20%. Any disagreement between a theoretical prediction and experiment is giving information. Before disregarding this information, one should look for a visible signal in the noise.

A useful example of how interesting physics can be learned from the interplay of experimental data and the predictions of theoretical models is given by hadron spin splittings. The first attempt to understand spin splittings in terms of an interaction between quarks was the 1966 model of Federman, Rubinstein and Talmi[5] who obtained the well known relation for the $\Sigma\Lambda$ mass difference in terms of other hadron masses (before De Rujula, Georgi and Glashow).

$$M_\Sigma - M_\Lambda = \frac{2}{3}\{(M_\Delta - M_N) - (M_{\Sigma^*} - M_\Sigma)\} \tag{1a}$$

This can be rewritten in a form which exhibits the underlying physics more clearly.

$$(M_\Delta - M_N) = (1/2)(2M_{\Sigma^*} + M_\Sigma - 3M_\Lambda) \tag{1b}$$

The Δ-N mass difference appearing on the left hand side expresses the spin dependence of the force between two nonstrange quarks under the assumption that the spin splitting is given by two body quark-quark forces. The hyperon masses on the right hand side of Eq. (1b) depend on forces between both nonstrange quark pairs and strange-nonstrange pairs. However the particular linear combination on the right hand side of (1b) eliminates the contribution from the strange-nonstrange pairs leaving only the same spin dependence of the force between nonstrange pairs appearing on the left hand side. Experimentally the values of the left hand side and the right hand side are 307 MeV and 294 MeV, thus showing that the spin dependent interaction between nonstrange quarks is the same in the nonstrange baryons and in the hyperons.

It is interesting that very similar results were obtained at about the same time by Zel'dovich and Sakharov.[6] However this paper has been overlooked because it was mainly concerned with the statistics problem in baryons and proposed a $(4q,\bar{q})$ structure for baryons.

The same model gives an equality between the spin splittings in the Σ and Ξ hyperons

$$(M_{\Sigma}*-M_{\Sigma}) = (M_{\Xi}*-M_{\Xi}) \tag{2}$$

This relation depends only on the spin dependent part of the force between a strange and a nonstrange quark since the two identical quarks in all of the baryons appearing in Eq. (2) are always in the spin triplet state and the spin dependence of this interaction does not contribute to the relation (2). The experimental values of the left hand and right hand sides are 192 MeV and 216 MeV. This 12% discrepancy can be dismissed as not important in a model which should only be expected to work to 10 or 20%. However once can still look for physics in this discrepancy. One can ask why the interaction between u and d quarks is very nearly the same in nucleons and hyperons, while the interaction between a strange and a nonstrange quark seems to be a little bit different in the Σ and Ξ baryons. We shall return to this question.

The results (1) and (2) follow only from nuclear shell model physics with purely phenomenological spin dependent interactions. What more can we learn from introducing QCD? De Rujula, Georgi and Glashow say that the spin splittings come from a color-magnetic hyperfine interaction proportional to the product of the color magnetic moments of the quarks involved. These color magnetic moments are assumed to be proportional to the electromagnetic magnetic moments with the electric charge replaced by a color charge. Like the Bohr magneton, they are inversely proportional to the quark mass. With this picture, the ratio of the spin splittings in strange and nonstrange baryons can be expressed in terms of the ratios of magnetic moments or masses.

$$\frac{M_{\Sigma}*-M_{\Sigma}}{M_{\Delta}-M_{N}} = \frac{\mu_s^{col}}{\mu_d^{col}} = \frac{\mu_s^{EM}}{\mu_d^{EM}} = \frac{m_u}{m_s} \tag{3}$$

where μ_f^{col}, μ_f^{EM} and M_f denote the color and electromagnetic magnetic moments and the mass of a quark of flavor f.

Since the strange quark is heavier than the nonstrange quark, this immediately predicts that the Δ-N splitting is larger than the Σ^*-Σ splitting and that the Σ is heavier than the Λ. It also predicts the magnetic moment of the Λ in the simple quark model for hadron magnetic moments which breaks SU(3) symmetry only by giving different values to the magnetic moment of the s and d quarks which have the same electric charge.

$$\mu_{\Lambda} = -\frac{1}{3}\mu_p \left(\frac{\mu_s^{EM}}{\mu_d^{EM}}\right) = -\frac{1}{3}\mu_p \frac{M_{\Sigma}*-M_{\Sigma}}{M_{\Delta}-M_{N}} \tag{4}$$

This prediction which gives -0.61 nuclear magnetons is in exact agreement with the experimental value.

Another independent prediction of μ_Λ follows[3] from the assumption that[6,7]

$$m_s - m_u = M_\Lambda - M_N \tag{5}$$

This also gives the same exact value $\mu_\Lambda = -0.61$. The underlying physics is discussed below.

We now return to the problem of why the relation (1b) for spin splittings of nonstrange quark pairs works better than the prediction (2) for strange-nonstrange pairs. One might first think that hyperfine interactions depend inversely on masses and would be smaller in states of higher mass. This qualitatively fits the small discrepancy in the nonstrange hyperfine interaction (1b) but has the wrong sign to explain the discrepancy in the relation (2). Another possibility is to note that the hyperfine interaction has a very short range and should increase with increasing mass of the constituents since states of higher mass quarks have a smaller size. But this effect should occur in both predictions (1b) and (2).

The paradox is solved by the Isgur-Karl model[2] for treating states of three quarks with unequal masses, its two internal degrees of freedom are the relative motion of the two identical quarks described by the ρ coordinate and the motion of the odd quark relative to the center of mass of the two identical quarks described by the λ coordinate. In the strangeness -1 hyperons appearing on the right hand side of Eq. (1b), the motion of the two nonstrange quarks described by the ρ coordinate has the same masses and forces as a nonstrange pair in the nucleon. The mass difference between the strange and nonstrange quarks affects only the part of the wave function described by the λ coordinate which is irrelevant for Eq. (1b). However in the Σ and Ξ hyperons appearing in Eq. (2) the relative motion of the two strange-nonstrange pairs involves both the ρ and the λ coordinates. The motion in the Ξ has a smaller radius than in the Σ because of the higher mass. Thus, the hyperfine splitting in the Ξ is bigger. The Isgur-Karl treatment of baryons containing quarks with equal masses has just the right qualitative features to explain the difference between the validity of the relation (1b) and the discrepancy in the relation (2).

III. Scales, Relativity, Approximations and Models

Constituent quark models for hadrons have been compared with analogous constituent models for atoms and nuclei. But there are important differences, characterized by a set of different scales. Any bound state has several features with the dimensions of length or mass: 1) the mass of the bound state or its Compton wave length; 2) the size of the bound state or the Bohr radius; 3) the excitation energy for orbitally excited states; 4) the fine or hyperfine structure arising from spin-dependent interactions. These four mass scales are listed in Table I for four different bound state models.

Table I

Scales of Bound States

Bound States	Mass M	Size $\hbar c/r$	Excitation Energy ΔE	Hyperfine Energy
Positronium	1 MeV	1/137 MeV	$1/(137)^2$ MeV	$1/(137)^3$
Nuclei	A GeV	50-100 MeV	5-10 MeV	——
Hadrons	1 GeV	200 MeV	600 MeV	300 MeV
Electrons	1/2 MeV	>>1 GeV	>>1 GeV	?

In atomic physics, represented by positronium as the simplest system bound by atomic forces with all constituents having equal masses, the four scales decrease monotonically in steps of 1/137. In nuclei the scales decrease monotonically in steps of about an order of magnitude. But in hadrons these scales are all approximately equal, and the excitation energy is larger than the energy defined by the size. Also listed are electrons, which are not relevant to baryon spectroscopy, but are included for completeness, since models have been proposed which attempt to describe quarks and leptons and bound states of even tinier objects. The scales for these models are completely opposite to those of conventional bound states. A number of very peculiar difficulties remain to be resolved, which are not discussed further here.

These scales have implications for the validity of the nonrelativistic approximation. A particle moving in a nonrelativistic orbit has a $v/c \ll 1$. But the velocity is just the product of the radius r and the angular velocity ω, and this angular frequency in a quantum system is related to the orbital excitation energy ΔE. Thus[4]

$$\frac{v}{c} = \frac{r\omega}{c} = \frac{r\Delta E}{\hbar c} \tag{6a}$$

This hand-waving derivation can be made rigorous by using the Heisenberg equations of motion and some matrix algebra to obtain

$$\frac{v^2}{c^2} = \frac{\dot{x}^2}{c^2} = \frac{[H,x]^2}{-\hbar^2 c^2} = \frac{(\overline{\Delta E})^2}{\hbar^2 c^2} \quad x^2 \tag{6b}$$

where x is the coordinate of a constituent, $\dot{x}$ is its time derivative, H is the Hamiltonian of the system, and $\overline{\Delta E}$ is some mean excitation energy for states of opposite parity from the ground state. Thus ΔE must be greater than the excitation energy of the lowest odd parity excitation. This gives v/c of order 1/137 for positronium, 1/10 for nuclei but unity for hadrons. Thus any model for a hadron which fits both the size of the proton as measured by its mean square radius and its excitation spectrum as measured by the excitation energy of its first odd parity N^* cannot be nonrelativistic. This statement is model-independent.

How can we then justify the use of a nonrelativistic quark model? It is an expansion in a "small" parameter, v/c, which is manifestly not small. But we have encountered this phenomenon before in physics. In the old days, when we learned quantum electrodynamics from Heitler's book, we calculated results to lowest order in perturbation theory and found good agreement with experiment, even though perturbation theory was obviously no good and higher order corrections were infinite. But the parameters used in the perturbation theory were not fundamental parameters in a theory from first principles. They were phenomenological parameters fitted to the experimental values of the charge and mass of the electron. Subsequent developments in renormalization showed that the use of these phenomenological parameters, rather than bare parameters, automatically included infinite sums of higher order terms. We therefore assume that something similar may eventually justify the simple nonrelativistic quark model which also uses phenomenological parameters. There may be something in it which we do not yet understand. Perhaps some hidden principle of relativistic regularization, asymptotic relativistic freedom etc. will eventually be derived and explain why the model works. Meanwhile we use the same approach of all unjustified perturbation expansions. Calculate the first non-trivial term, throw the rest away without looking at it, and compare with experiment.

Why do we need different models to describe baryon structure? Because nobody knows how to solve the relativistic three-body problem remaining even after the glue and the ocean of pairs are neglected. Simplified models are invented which can be solved, each at the price of omitting some of the physics. Different models emphasize and omit different physics and are useful for different types of data; namely those where the physics omitted is not important. The M. I. T. bag model[8] reduces the relativistic three-body problem to a relativistic one-body problem. It is useful for testing relativistic effects, but neglects two-body correlations of the type successfully demonstrated in the calculation of the neutron charge radius and in the Isgur-Karl treatment of strange baryons with unequal mass quarks. The harmonic oscillator shell model is nonrelativistic, but furnishes a shell model which can be solved exactly and which includes two-body correlations. It is the only model in which the center-of-mass motion is treated exactly and spurious excitations are simply separated. Another potential model which has been used is the Quigg-Rosner logarithmic potential.[9] Although this potential is not tractable for the three-body problem, many results are obtained without full calculations using the scaling properties of the potential; in particular results relating meson and baryon spectra.

In evaluating results from different models, we should keep track of the physics that is left out or distorted by the model. The harmonic oscillator potential is much flatter at short distances than a more realistic Coulomb potential, and is rising much too rapidly at long distances than a linear confining potential. Thus the harmonic oscillator wave functions may be good for global properties of baryons, but may not be useful at very short and at very long distances. This is most simply expressed by noting that the harmonic oscillator wave functions are gaussians in both configuration and momentum spaces, and therefore drop off very rapidly both at large distances and at high momenta. A more realistic wave function does not drop off as rapidly as a gaussian in either configuration or momentum space. Thus one should expect the tails of the wave functions to extend farther out in both spaces than predicted by the harmonic oscillator wave functions, and any results which are very sensitive to these tails should be carefully scrutinized.

The logarithmic potential also deviates from the expected potential by not being singular enough at short distances and not confining enough at large distances. It should therefore be better than the harmonic oscillator for short distances, and err in the opposite direction from the oscillator at large distances. Note, however, that in the three-body problem, the effective potential seen by one quark is smeared by the motion of the other quarks, and singularities are smoothed into something more like an oscillator.

IV. Are Mesons and Baryons Made of The Same Quarks?

The baryon spectroscopy meeting should not be allowed to avoid mentioning the heretical work meson. We believe that mesons and baryons are made of the same quarks interacting with the same gluons via QCD. Can these interactions between constituent quarks be described by the same two-body interaction without the need for three-body forces? Using an effective interaction approach similar to that used in nuclear physics (and originally by Bacher and Goudsmit for atomic physics), we encounter two problems in providing a unified treatment of mesons and baryons. The quark-quark force in baryons must be related to the quark-antiquark force in mesons, and the scaling of the wave functions which have different sizes must be taken into account. The use of a color exchange force and the scaling properties of the Quigg-Rosner logarithmic potential[9] enable unambiguous prescriptions to be made for relating meson and baryon spectra,[7,10] and these have had remarkable success.

The assumption that the flavor dependence in hadron spectra comes only from quark masses and hyperfine interactions[6,7] enables the mass difference between the strange and nonstrange quarks to be determined from both meson and baryon spectra. Taking linear combinations which project out the contribution of the hyperfine interaction the following result was obtained:

$$m_s - m_u = M_\Lambda - M_N = \frac{3}{4}(M_{K^*} - M_\rho) + \frac{1}{4}(M_K - M_\pi) \tag{7}$$

This result was used in Ref. 3 to obtain the prediction (5) for the magnetic moment.

A number of relations between meson and baryon spectra have been obtained by plugging in the two-body interaction which fits the charmonium spectrum into the baryon Hamiltonian with no free parameters.[10] A recent surprising result is the difference between the "effective quark mass" in the baryon and the meson, defined as

$$m^q_{eff}(\text{baryon}) = \frac{M_\Delta + M_N}{6} \tag{8a}$$

$$m^q_{eff}(\text{meson}) = \frac{3M_\rho + M_\pi}{8} \tag{8b}$$

These are the linear combinations of masses which project out the contribution of the hyperfine interaction, divided by the numer of quarks. The simple model predicts

$$m^q_{eff}(\text{baryon}) - m^q_{eff}(\text{meson}) = \frac{U_o}{2}\log(2/\sqrt{3}) = 53\text{ MeV} \tag{9}$$

where U_o is the Quigg-Rosner constant from the charmonium spectrum. The experimental value is 54.5±1.5 MeV.

V. Multiquark Spectroscopy

The hyperfine interaction has also been extensively used in multiquark spectroscopy, where its crucial role was first pointed out by Jaffe.[11] The color electric force between two color singlet hadrons vanishes, like the force between two neutral atoms, and does not lead to binding of multiquark systems. But the hyperfine interaction does not saturate in this way, and multiquark systems can be bound by the hyperfine interaction if the spins and colors of the constituents are suitably coupled. The S^* and δ scalar mesons at the $K\bar{K}$ threshold can be considered as a $K\bar{K}$ pair bound by the hyperfine interaction. The existence of a whole set of such "threshold exotics" has been suggested[12,13] in which recoupling of quark color and spin in a two-hadron state can produce a bound state with exotic quantum numbers. One possibility of interest to baryon spectroscopyc is an anticharmed baryon consisting of four quarks and a charmed antiquark. Such a state could not decay into an ordinary charmed baryon because of the wrong sign of charm. It it is below the threshold for decay into a charmed meson and an ordinary baryon, it would be stable against strong decays and be a very interesting object.

Malcolm Harvey[14] has pointed out that the hyperfine interaction is sufficiently strong in the six quark system to completely reverse the intuitive picture in which the lowest configuration is s^6 with all of the quarks in the lowest s shell. The s^4p^2 configuration can be lower, because promoting two particles into the p shell gains more hyperfine energy than is lost by promoting the orbital excitation. Quantitative calculations of this effect are difficult, because a hyperfine interaction which is as strong as the orbital excitation energy cannot really be treated as a perturbation on unperturbed orbits. But higher order calculations with the very singular Fermi-Breit hyperfine interaction are impossible and a more fundamental description with gluon exchange is required. However, this effect cannot be ignored and may introduce drastic changes in multiquark calculations, particularly those attempting to obtain the nucleon-nucleon force from quark dynamics.

Multiquark spectroscopy has been very much confused by the baryonium fiasco. This is an example of how the bag model should not be used. Large numbers of states were predicted and the literature was then searched for experimental evidence for such states. Unfortunately there was not sufficient feedback from the real world, both on the theoretical and on the experimental sides. The result was a wild goose chase which ended with most of the so-called experimental evidence for baryonium disappearing as statistical fluctuations.

The theoretical model of an elongated bag with two clusters of quarks at the ends, each with well defined quantum numbers, has no theoretical or phenomenological basis. The stability of the individual clusters is very questionable. The interactions between the quarks in one cluster and the quarks in the other are just as strong as the interactions between the quarks in a given cluster. Analogies with molecular physics and color chemistry are misleading,[4,7,13] because the forces which bind atoms into molecules are very much weaker than the Coulomb forces which bind electrons and nuclei into atoms, while the color-electric forces between quarks in a two-cluster multiquark system are all of the same order of magnitude if the individual clusters are not color singlets. Quark exchange or color exchange between clusters can easily occur as well as simple breakup of the clusters. The hand-waving argument that centrifugal barriers keep the clusters apart should not be simply extrapolated from the two-body problem to the n-body problem. The barrier does not prevent breakup of the clusters and exchange of particles between them, as long as enough of the cluster remains at large distances to carry the angular momentum.

One baryonium model on very shaky theoretical grounds has a color sextet diquark and a color sextet antidiquark kept apart by a centrifugal barrier. There are two serious objections to this model: 1) color exchange between the diquarks mixing it with the state of a color triplet diquark and a color triplet antidiquark; 2) breakup of the diquarks because the color-electric force between the quarks is repulsive. A diquark-antidiquark pair in a color singlet must have color correlations and color oscillations which can only be produced dynamically by gluon exchange.[15] A state of two red quarks and two red antiquarks is not a color singlet. The colors of the quarks and antiquarks must be changing continuously at a very high frequency in order to produce a color singlet state. These color exchanges mix the color sextet and color triplet diquark states.

The color electric force due to one gluon exchange between quarks is repulsive in the color sextet state.[16] If the force between the two quarks is repulsive, the diquark sextets must break up and cannot form baryonium. One can argue that one gluon exchange is not adequate and that higher order corrections could give an attractive quark-quark force in the color sextet state. But if the quark-quark force is attractive in all channels there are difficulties with saturation. There is no stable diproton. But when two protons are brought close together, there are nine new quark-quark pairs which can attract if there is an attractive qq force in all color states. Even if the qq bond is only 5 MeV in the weakest attractive state, the diproton would be bound by 45 MeV. This clearly rules out attractive interactions between quarks in the color sextet state. Some repulsive force is necessary to cancel out the attraction in the color singlet state to prevent the binding of the diproton.

Multiquark spectroscopy can be revived after the baryonium fiasco by keeping one's feet on the ground and using sounder models and experiments. Convincing evidence for multiquark states can come from unambiguous signatures, such as

1. Exotic quantum numbers - including the anticharmed baryons discussed above.

2. Exotic decay modes forbidden for normal 3q baryons; e.g. $N\phi$.

3. Peculiar systematics in decays; as in the R baryon (3.1 GeV) which likes to decay with an additional strange quark-antiquark pair.[17]

So far the R baryon remains an interesting puzzle, with no good theoretical description. It is much to narrow to be a standard $4q\bar{q}$ exotic at such a high mass. Since the mass is below that of three strange baryons, it might conceivably be a $BB\bar{B}$ bound state with the antiquarks sufficiently far away from the quarks to inhibit a rapid decay by rearrangement into mesons. If the R is really a nine quark object, its decays should be primarily into nine-quark states; i.e. one baryon and three mesons, and decays into one baryon and one or two mesons should be suppressed. Present data support this conjecture, but are not convincing because the failure to observe one and two meson modes may be a matter of experimental acceptance. Further investigation of the properties of the R, including the multiplicity distribution of the decay products, would help to clarify this point. If the R is really a resonance and doesn't go away like baryonium, it might be the beginning of a new kind of spectroscopy. Considerable effort to tie this down would be very much worthwhile at this time and experimentalists should be keeping their eyes open for other similar objects.

It is instructive to compare the charmonium success with the baryonium fiasco. As soon as the J/ψ was discovered, there was no further question about its existence because the experimental evidence was so clear. But it took some time before the theorists accepted its identification as charmonium. Everything about charmonium had been known and predicted by theorists, except for one crucial ingredient which is the key to charmonium spectroscopy; its narrow width. Theorists believed that charmonium would be something like strangeonium, where only the lowest vector and tensor states (ϕ and f') are unambiguously identified today eighteen years after the discovery of the ϕ. They suggested that naked charm would be much easier to find experimentally and interpret than charmonium. The one point missed by the theorists prevented them from suggesting any of the highly successful experiments in charmonium spectroscopy beginning with the discovery of the J/ψ. Without the narrow width, none of these states would have been seen very easily, and their identification would have been bogged down in the same kine of uncertainties that have plagued the identification of the A1, ρ' and ϕ'.

The baryonium fiasco involved theoretical advice taken too seriously by experimentalists and unclear experiments taken too seriously by theorists rather than very convincing experiments which were not understood. Perhaps the R baryon is a step in the right direction. But as long as experimentalists talk about how many standard deviations the effect is it remains dubious. Nobody talked about the number of standard deviations in the data which discovered the J/ψ.

VI. Open Problems Baryon Magnetic Moments

Conventional three-quark baryon spectroscopy seems to be well described by the Isgur-Karl model, but this does not imply that the field is finished. The model explains enough to be taken seriously. But a consistent picture of how well it works in different areas can still teach us some physics. Meanwhile there should also be new predictions, either for smaller higher order effects where the lowest order seems to work, or for new effects not yet considered. New channels for production and decay should be considered in addition to the pseudoscalar meson-baryon channel.

Photoproduction experiments give information on the vector meson-nucleon channel

$$\gamma p \rightarrow \rho, \omega, \phi + N \tag{10a}$$

There have also been reports on meson production in pp collisions, which can be interpreted as meson-proton scattering[18]

$$pp \rightarrow pp\ M\ , \tag{10b}$$

where M is any neutral meson. If this reaction is studied in the kinematic region appropriate to M exchange, then the process of Mp scattering is studied. The particular case of ω production via ω exchange has been reported with information about ωp resonance. This state should be described by the Isgur-Karl model and predictions for the ωp decay mode should be given.

So much still remains to be done in conventional baryon spectroscopy. A new open problem in baryon spectroscopy has been indicated by Overseth's report on new measurements of baryon magnetic moments.[19] The remarkable agreement with the naive quark model of the new value of the Λ magnetic moment discussed above was not duplicated in the case of the other hyperon magnetic moments, which are being measured with great precision by the hyperon beam group at Fermilab. The simple model of adding vectorially the magnetic moments of the three quarks to get the baryon magnetic moment does not work for the Σ and Ξ moments to the precision attained in the nucleon and Λ.

A simple way to present the situation is to note that the nucleons, charged Σ's and Ξ's all consist of two quarks of one flavor, which we denote by a, and an odd quark of a different flavor, which we denote by b. If we assume that the contribution of each quark to the hadron magnetic moment is proportional to its charge q and inversely proportional to its mass, we can write a general expression for the magnetic moment,

$$\mu(aab) = (q_a/m_a)\gamma_2 + (q_b/m_b)\gamma_1 \tag{11}$$

where γ_2 and γ_1 are coefficients depending upon the wave functions of the baryons. For the simple model in which there is no orbital angular momentum and the two quarks of the same flavor are required by Fermi statistics of colored quarks to be in the spin singlet state, $\gamma_2 = 4/3$ and $\gamma_1 = -1/3$. These values are uniquely determined by the angular momentum couplings and are used in all the simple quark model predictions.

If we leave the values of γ_2 and γ_1 as free parameters, the expression (11) is valid for any baryon three-quark wave function with arbitrary configuration mixings. The values of γ_2 and γ_1 will then be determined by the wave functions. However, it seems reasonable to assume that isospin is a good symmetry, so that the values of γ_2 and γ_1 are the same in the two states which go into one another under isospin reflection. We further assume isospin symmetry at the quark level, $m_u = m_d$, and the conventional values of quark charges. Thus

$$(q_u/m_u) = -2(q_d/m_d) = -2(m_s/m_d)(q_s/m_s) \approx -3(q_s/m_s) \tag{12}$$

where the last equality is obtained by setting $m_s/m_d \approx 3/2$ which is approximately the accepted value for constituent quark masses.

Franklin[20] derived a number of sum rules for magnetic moments and has pointed out that the assumptions (11) and (12) lead to relations between magnetic moments which are in disagreement with experiment, thereby showing that the failure of the simple quark model to explain the data cannot be fixed by simple configuration mixing. This is most easily seen by constructing the linear combinations of magnetic moments of isospin mirror states which project out γ_1 and γ_2,

$$(1/4)(M_p/m_u)\gamma_2^{Nd} = (1/4)(\mu_n+2\mu_p) = 0.92 \tag{13a}$$

$$(1/4)(M_p/m_u)\gamma_2^{\Sigma d} = (1/4)(\mu_{\Sigma^+}-\mu_{\Sigma^-}) = 0.95\pm0.1 \tag{13b}$$

$$(M_p/m_u)\gamma_2^{\Xi s} = -(m_s/m_u)(\mu_{\Xi^o}+2_{\Xi^-}) = 1.03\pm0.05 \tag{13c}$$

$$-(M_p/m_u)\gamma_1^{Nd} = -(\mu_p+2\mu_n) = 1.03 \tag{14a}$$

$$-(M_p/m_u)\gamma_1^{\Sigma s} = (m_s/m_u)(\mu_{\Sigma^+}+2\mu_{\Sigma^-}) = (3/2)(-0.63\pm0.74) \tag{14b}$$

$$-(M_p/m_u)\gamma_1^{\Xi d} = \mu_{\Xi^-}-\mu_{\Xi^\circ} = 0.49\pm0.07 \tag{14c}$$

where γ_i^{Hf} denotes the value of γ_i in the hadron isospin multiplet H, and f denotes the flavor of the relevant contributing quarks. The six quantities (13) and (14) have been normalized to make them all equal in the naive quark model without orbital angular momentum, and with the value

$$(1/4)(M_p/m_a)\gamma_2 = -(M_p/m_b)\gamma_1 = (1/3)\mu_p = 0.93 \tag{15}$$

The outstanding discrepancy in these values is in the contribution of the odd nonstrange quark to the Ξ moment, Eq. (14c). Note that the contribution of the two strange quarks to the Ξ, Eq. (13c) is in reasonable agreement with the simple model. The large errors on the Σ^- moment hide another discrepancy. The present value of Eq. (14b) is in strong disagreement with the model, but is not statistically significant. However, this value is strongly correlated with Eq. (13b). If better measurements of the Σ^- moment raise the value of (14b) to bring it closer to the values (14a) or (14c), the value of (13b) would be lowered significantly to bring it into disagreement with (13a) or (13c).

The main conclusion from these discrepancies is that better values for the moments, in particular the Σ^-, are needed before real conclusions can be drawn about any modification of the simple model. Such a modification must reduce the contribution of the odd nonstrange quark in the Ξ by a considerable factor, but without appreciably changing the contribution of the two strange quarks in the Ξ (13c). Any model which achieves this in the Ξ would naturally tend to reduce the contribution of either the nonstrange quarks or of the odd quark in the Σ as well. This again shows that a better value of the Σ^- moment is needed to distinguish between discrepancies in the contribution of the nonstrange quarks (13b) or the odd strange quark (14b).

Configuration mixing can explain the results (13) and (14) only if the mixing is very different in the N, Σ and Ξ systems. This requires SU(3) breaking, and a mixing of an SU(3) decuplet via the SU(3) symmetry breaking part of the tensor force has been suggested as a way to fix the Σ and Ξ without destroying the good results for the nucleon and Λ which cannot be mixed by this mechanism.[21] Reduction of effective quark magnetic moments in hadrons by mass factors[22,23] has also been suggested with the justification of expressing the moments in magneton units appropriate for each hadron. However, the results (13) indicate no such reduction for the two identical quarks. Brown and Rho[24] have suggested that a two-body pion-exchange diagram would produce an additional isovector contribution to the nucleon magnetic moments, which would be absent in the hyperons. Removing this contribution from the experimental nucleon moments reduces the values of (13a) and (14a) for the single nonstrange quark contribution and brings these values closer to (14c), thereby also destroying the good agreement with (13b). Again we see that the large errors on the Σ^- prevent a significant test of the model.

Charmed baryon spectroscopy is still a young field, with new evidence confirming the existence and properties of the Λ_c, Σ_c and Σ_c^*, but a long ways to go before we have any real understanding of the structure of these baryons. New techniques will be needed to accumulate statistically significant data, now that we have a small but sufficient number of events to be convincing that the states really exist.

In conclusion, I should like to remind everyone that baryon spectroscopy is not an isolated island. Mesons are made out of the same quarks as baryons, nuclei are made out of baryons, and the same stuff is found in cosmic rays and stars. There is considerable interest in "interdisciplinary investigations" of how baryon physics fits together with meson and nuclear physics and astrophysics. This includes the rudimentary attempts to obtain the nucleon-nucleon force from baryon physics, the "Brown bag" which attempts to combine the pion field found in nuclei with baryon physics, the use of baryon wave functions to study proton decay, and various attempts to make exotic multiquark matter. Perhaps there will be exciting new things in these areas by the next baryon conference.

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